Science and Technology Goals of the Teapot Dome Field Experimental Facility

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Abstract

The new Teapot Dome facility presents a unique opportunity to conduct carbon-storage experiments across many geological conditions and scientific disciplines. The field is fully owned by the US government and operated by the Rocky Mountain Oilfield Testing Center, which provides a stable platform for investigation. Target reservoirs, both oil & water bearing, range from 500' – 8000' depth and represent diverse rock, brine, and hydrocarbon compositions and configurations. Initially, the facility will focus on three scientific concerns:

- Storage: Important uncertainties in total storage capacity include irreducible saturation, mixing mechanisms, brine/fluid/rock interactions, multi-phase fluid flow, reservoir heterogeneity, and other factors. *The first storage experiment proposed at Teapot Dome will inject CO_2 into a depleted oil reservoir at 5500' with the intent of maximizing in situ storage (not maximizing hydrocarbon recovery).*
- Leakage: For geological storage to succeed internationally, it will require a sophisticated understanding of the volume, rates, locations, & probability of CO_2 leaks along pre-existing wells and natural fast paths (e.g., faults or high permeability stratigraphic leaks). *The first leakage risk experiment proposed will attempt to induce leakage from a shallow reservoir (< 2200') along faults to the surface.*
- MMV technology: For wide-scale deployment of CO_2 storage projects, public safety requirements, market & legal concerns, and scientific advancement will likely require a suite of calibrated MMV approaches. *All experiments will engage multiple geophysical & geochemical monitoring approaches.*

We hope facility use will expand for international collaborations, for experimentation, for technology transfer and training, and as a site to test novel concepts.

Introduction

Carbon capture and storage (CCS), or carbon sequestration, has become a critical and increasingly important component of plans to reduce greenhouse gas emissions (e.g., US DOE 2003, US CCTP 2003, IPCC in review). Specifically, storage of carbon dioxide in geological reservoirs has become a primary focus of industrial, academic, and government research (e.g., US DOE 1999; IEA 2002; IPIECA 2003). Due to economic, policy, and engineering concerns, a great deal of effort has focused on these sectors. However, concerns about the mechanics and uncertainties associated with subsurface injection and trapping (the "tailpipe") have prompted efforts to generate new knowledge that would help demonstrate the safety, ease, cost, and efficacy of geological carbon storage (e.g., US DOE 2003; Hawkins, 2003).

Ultimately, much of this new knowledge will come from the study of large field projects (Friedmann, in press). Some of these are demonstration projects, such as Sleipner and Weyburn (e.g. Torp & Gale 2003, Preston 2003). The primary project goal is to store large CO_2 volumes. In that context, scientific and technological research proceeds in the context of project economic and operational concerns. Some CO_2 sequestration projects are intimately linked to enhanced oil recovery; in those cases both injection scenarios and monitoring technologies are focused on optimization of oil production. Other projects are field experiments, such as the Frio Brine Pilot (Hovorka et al. 2003, Myer et al. 2003). The goal here is to develop knowledge through scientific experimentation. In that context, the primary limits to investigation come from geological constrains, budget, ownership, and the regulatory framework.

Both approaches are important and have produced important learnings, yet both have limitations. For field experiments, the high cost of CO_2 and typically limited *in situ* geological data makes a large-scale project extremely expensive. However, by working at a small scale, important questions regarding the scale and impact of subsurface heterogeneities (e.g., faults, large permeability baffles, cementation, etc.) cannot be adequately addressed (Friedmann, in press). Similarly, the economic and proprietary drivers in large demonstration projects have ultimately limited scientific scope and created tensions that inhibit the generation and distribution of new results. To resolve these difficulties will ultimately require a large-scale, high budget, dedicated field experimental facility.

Towards that end, the US Department of Energy (US DOE) has designated Teapot Dome oil field as a national geological carbon storage test center (Figure 1). This is the only oil field currently owned by the US Federal Government. This makes it possible to propose and initiate scientific experiments and technical development programs within a long-term, stable business context and absent the commercial drivers of a privately owned oil field. This paper describes the science goals of the effort at Teapot Dome and the preliminary science plan.

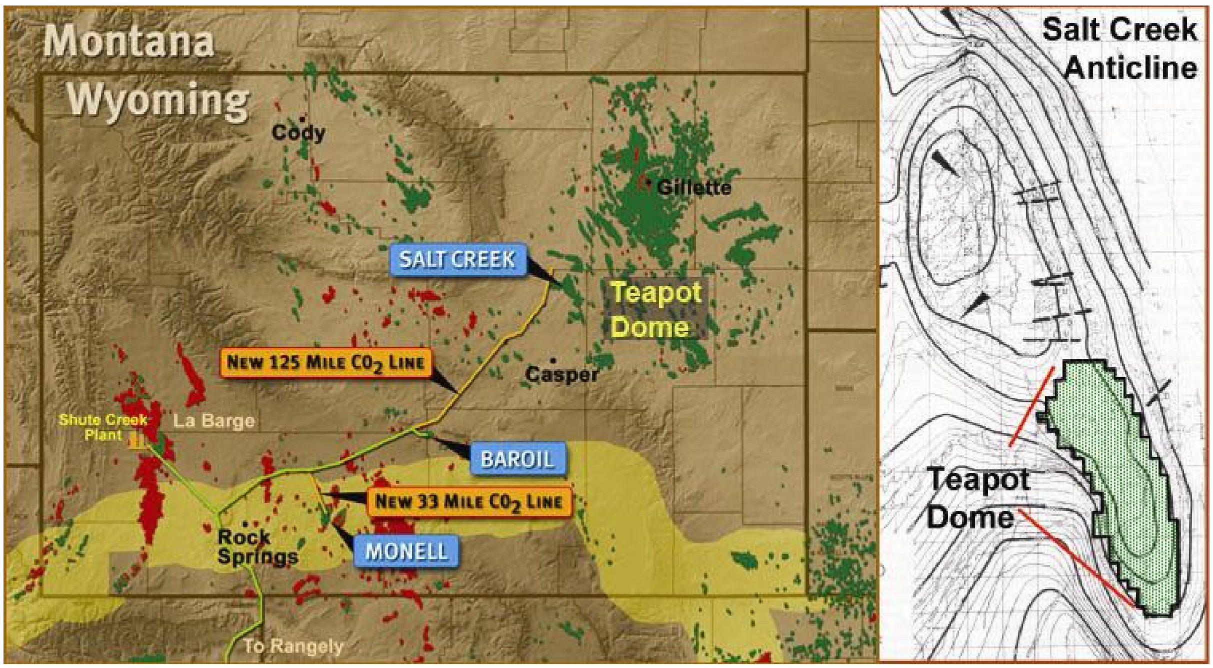

Figure 1: Location for Teapot Dome. (Left) Shaded Relief map of Wyoming with location of CO_2 pipelines Dashed orange lines were completed in early 2004; dashed blue line is proposed extension. Red areas are large gas fields, and green areas are large oil fields. Image courtesy of Anadarko Petroleum Corporation. (Right) Structure map on the top 2nd Wall Creek Sandstone at the Salt Creek and Teapot Dome oil fields. Heavy line and green field show field boundaries. Small squares = 1 mi^2

The Teapot Dome Field Experimental Facility

<u>Field History</u>

The new Teapot Dome facility presents a unique opportunity to conduct carbon-storage experiments, largely as a consequence of its history. The field was declared a Naval Petroleum Reserve (NPR-3) by the Wilson administration in 1915. Subsequently, it became the subject of a national scandal from 1923-1927 involving land deals, oil production, and the Harding administration. In 1927, the US Supreme Court shut production, and ordered that the money from sale of oil produced from the field would go directly to the US Treasury. This effectively stopped production and removed financial incentives from further production. NPR-3 was reopened to full development in 1976, and became a DOE facility in 1977.

RMOTC was established by the US DOE to partner with the petroleum industry to improve domestic oil and gas production through the field testing of new technology, evaluation of new equipment, and demonstration of new processes. It is the field test site of choice for companies and individuals involved in the development of leading edge oil and gas technology. RMOTC is the most comprehensive test site in the U. S. for field testing of upstream petroleum and environmental equipment, tools, and procedures, and provides testing partners a setting to evaluate performance characteristics (more information is available at RMOTC's website, www.rmotc.com).

Current field status

The field has over 1300 wells total. Of these, ~600 are currently producing, with an additional ~700 wells which are not producing. All cores, well-logs, mud-logs, completion descriptions, and production data from these wells are public domain. In addition, RMOTC acquired a 3D seismic volume over Teapot Dome in 2000. This public domain data set is key to mapping structural and stratigraphic attributes and heterogeneities at depth. Reports regarding drilling tests, water floods, and steam floods are also public domain.

Field infrastructure includes roads (paved & unpaved), pipelines and water lines, several buildings, telephone lines, and dedicated internet connections. Currently, RMOTC operates one drilling rig and 600 pump jacks of varying sizes. Drilling costs are covered by RMOTC, and an internal committee of scientists and engineers approves the drilling program.

As of April 2004, there is no dedicated CO_2 pipeline into Teapot Dome. However, Anadarko Petroleum Corporation has recently completed a new CO_2 pipeline to their Salt Creek field, immediately adjacent to Teapot Dome's north (Figure 1). The pipeline configurations provide for 250 million ft^3/day. RMOTC and the DOE are currently discussing the pipeline right-of-way, costs, and CO_2 price with Anadarko. Given this, the earliest date for initial CO_2 injection into Teapot is 2005, by truck if necessary. Pipeline delivery of CO_2 may not begin until 2006.

Scientific Goals

Various research and planning organizations have outlined critical scientific challenges in the carbon storage field (e.g. US DOE 1999, Klara et al. 2003, IPIECA 2003). These roadmaps and recommendations underlie the central scientific mission at Teapot Dome. Many of the chief uncertainties involved in carbon storage geoscience can be summarized as three broad questions:

- What is the true capacity of subsurface injection targets? This bears on site selection for plants and infrastructure, trading rubrics, and assessment.
- What are the risks to health, safety, and the environment associated with CO_2 leakage from subsurface targets? This bears on public perception, risk management, and regulatory agreements.
- What are the most cost effective approaches to monitoring and verifying injected CO_2? This bears on both of the above issues, as well as economic planning and general R&D.

These questions bear on concerns about economics, viability, and reliability of geological storage. As such, issues of regulatory framework, market mechanisms, and stakeholder acceptance will require scientific information to adequately answer these questions. The scientific goals of Teapot Dome reflect these important research areas.

During a plenary meeting in October 2003, over 33 researchers and administrators gathered in Casper, WY to discuss the primary scientific objectives for the field experiments. The recommendations of this group form the core of the proposed research. The first two experiments will study questions of capacity and leakage risk respectively. Both experiments, and future experiments, will involve suites of monitoring tools that operate across a wide range of geophysical and geochemical conditions.

Maximize Storage Capacity

Teapot Dome encompasses many different lithologies and potential subsurface targets. Nine of these are oil and gas bearing; at least another six are aquifers of varying salinity. Although we anticipate future experiments involving the aquifers, the initial focus will be on oil-bearing units, due to the economic drivers associated with carbon storage and the abundance of geological data in most hydrocarbon fields.

The first proposed reservoir target will be the Tensleep Fm. (Teable 1), with a structural crest at a subsurface depth of 5500'. At Teapot Dome, the Tensleep comprises aeolian sandstones, sabkha carbonates, evaporates (mostly anhydrite), and extensive beds of very low permeability dolomicrites. The Tensleep Sandstone accounts for about two-thirds of all oil produced in Wyoming, and many large accumulations elsewhere in the Rockies (e.g., the

Table 1: Tensleep Characteristics

	Average	2σ range
Porosity (f)	10	1 – 19
Permeability (mD)	30	0 – 110
Thickness (m)		
Salinity (mG/L)	3100	2600-3600
Gravity (API units)		

Rangely field in Colorado) produce from Tensleep equivalents (Nummedal et al., 2003). As such, the Tensleep Sandstone is currently a major target for enhanced oil recovery, and is likely to eventually store large volumes of CO_2. Baseline characterization to date includes core description, well-log correlation, petrographic study, fracture analysis, and outcrop description. These will serve as the basis for a static geological model, with a full-field flow simulation to follow.

Within Teapot's boundaries, over 33 wells have penetrated the Tensleep, including 13 cored wells. Many of these enter a small closure and hydrocarbon accumulation in the southern portion of the field. The closure is bounded by an oblique-slip fault to the north and otherwise dips away from the structural crest, covering an area of roughly 1 km^2. Because the closure is penetrated by only 14 wells (3 outside the closure), it is small enough to be manageable yet large enough to capture most of the critical reservoir heterogeneities. This proposed site is the focus of current investigation, and will ultimately lead to a proposal for injection well and monitoring suite.

Leakage Risk Characterization

Potential leakage risks may represent the largest concerns involved in carbon storage. This has resulted in demonstration projects where risk of leakage is extremely small. This setting greatly limits the ability of researchers to study the mechanics and dynamics of leakage. An engineered or induced CO_2 leak would provide researchers an opportunity to greatly improve prediction and understanding of the conditions typical of target failure. Towards this end, research efforts at Teapot Dome have focused on identifying the locations where one might safely engineer a CO_2 leak for scientific investigation. Such a site would have a high initial chance of success based on geological criteria and a large number of monitoring options.

The earliest petroleum prospectors in the region initially recognized Teapot Dome from hydrocarbon seeps at the surface (Wegemann, 1918; Thom & Spieker, 1931). Indeed, there is evidence of hydrocarbon seepage from the field along faults that crop out at the surface of the Dome. Several of these faults contain calcite veins that are stained with hydrocarbon residue, and some are the locus of alkali springs (Cooper et al., 2003). This led modern investigators to believe that Teapot might be suitable to study aspects of CO_2 leakage.

Subsurface and surface mapping with the 3D seismic volume and field expeditions revealed a series of oblique-slip fault networks that root into the basement (Figs. 2, 3). These appear to have accommodated differential deformation during the formation of the Dome roughly 75-55 million years ago, and have characteristics of a negative flower structure (Harding et al., 1986). Although they generally are oriented along a NE-SW trend, the faults vary in geometry, displacement, and complexity. In particular, one set of faults, here called the S2 network, shows great complexity and a range of

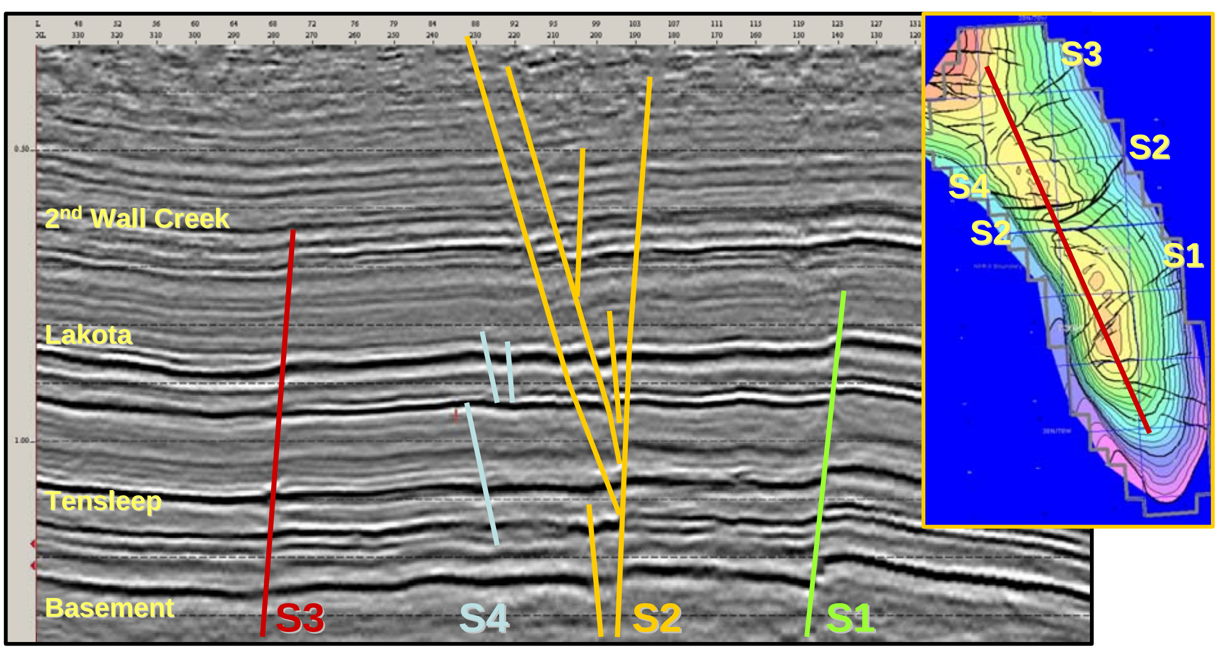

Figure 2. Arbitrary cross-section through Teapot Dome. The location map (inset) is a depth-structure map on the 2nd Wall Creek. Sandstone. One can see the great complexity of the S2 fault network, how multiple strands offset the 2nd Wall Creek, and how the faults appear to track to the surface.

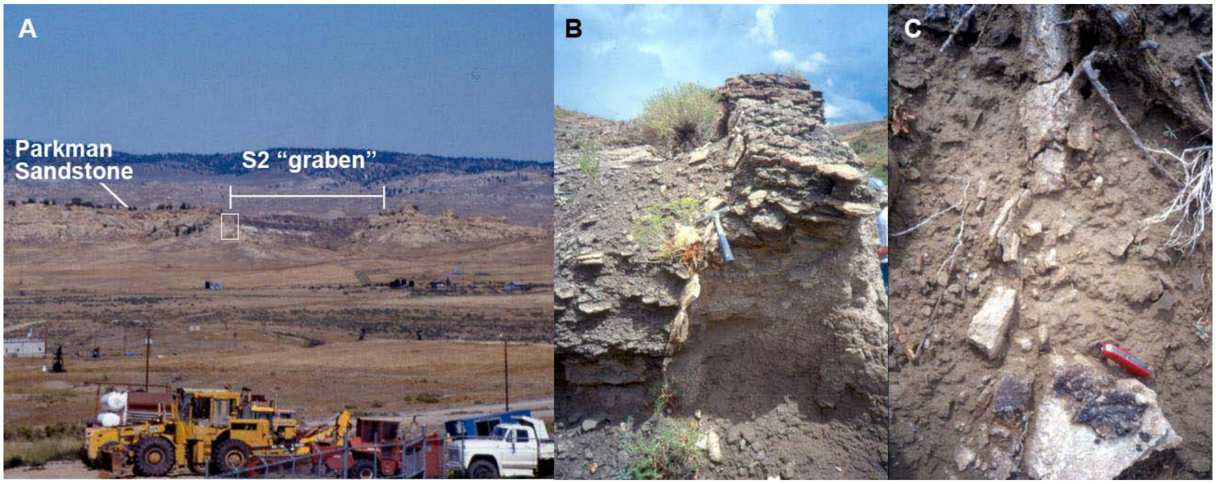

Figure 3: Example of surface expression of S2 fault network. (A) View to east of Parkman Sandstone ridge. Note that oblique slip faults have truncated and offset a portion of the ridge. (B) a close up of one S2 fault strand. Note calcite veins and apparent normal offset. (C) a close up of a fault vein in outcrop and float. The black substance in dead oil (hydrocarbon staining)

geometries and azimuths. This geologic range enhances the potential for leakage along the fault relative to other groups. Indeed, the fault zone crops out well within the field, supports alkali springs, and contains hydrocarbon samples within the fault veins and gouge. It is likely that this area will be the focus of the first leakage experiment proposal.

The fault zone truncates three oil-bearing units (Shannon Sandstone, 1st Wall Creek, and 2nd Wall Creek) depths between 500' and 2100'. The lowest of these reservoirs, the 2nd Wall Creek, is closest in terms of temperature and pressure to conditions of supercritical CO_2 phase injection and oil miscibility. In other fields within the structural trend, this reservoir is also the largest and is current the focus of EOR efforts, exemplified by Anadarko's efforts at CO_2 flooding of the 2nd Wall Creek at Salt Creek field. The depth to the 2nd Wall Creek, its CO2 miscibility potential, and its well-documented structural framework suggest that the central S2 area should receive the greatest effort in characterization for a proposed experiment. Currently, detailed fault mapping and fault seal characterization will serve as the basis for that decision.

In addition to the fault leakage effort, research has begun on well leakage risks. Part of this effort is proceeding in concert with the Carbon Mitigation Initiative at Princeton University, which is investigating well integrity from the perspective of cement dissolution. Due to the 80-year production and drilling history of the field, wells range widely in cement composition and character. The current effort includes subsurface sampling of cement within key target intervals across a range of well ages, cements, and configurations. Subsequent characterization of cements in terms of permeability and strength will be followed by geochemical experiments across various temperatures and CO_2 concentrations.

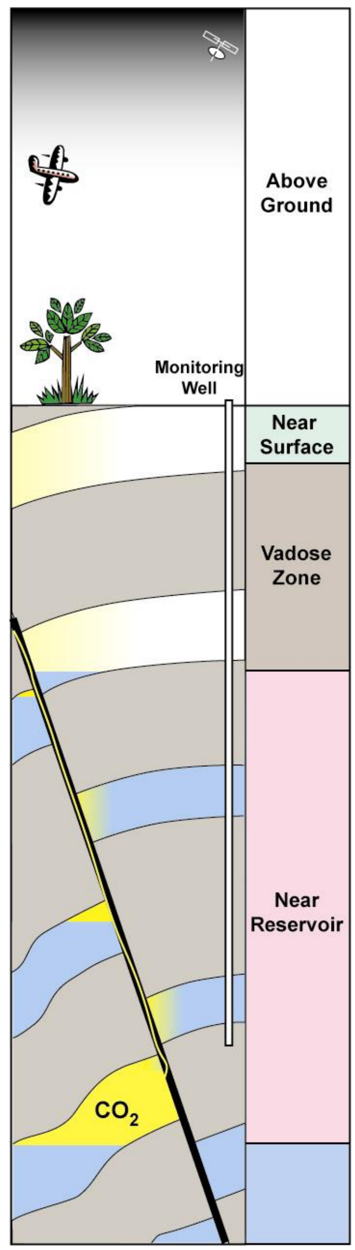

Figure 4: Key MMV domains.

Measurement, Monitoring, and Verification (MMV) Technology

Success in carbon storage requires that both injection and leakage be detectable within a range of key environments (Fig. 4). As such, MMV tools and technologies are vital to both scientific and commercial goals (e.g, US DOE 1999, Klara et al. 2003). These tools should work in four domains: near the reservoir, within the vadose zone, near the ground surface, and above the surface (Fig. 4). Since there is no single tool capable of working in all these domains, a set of MMV tools is required. Questions of detection threshold, resolution, signal interpretation, and cross-calibration between tools will prove important aspects of future research.

Currently, much research effort has focused on time-lapse (4D) reflection seismic imaging (e.g., Torp & Gale, 2002; Terrell et al., 2002; Davis et al., 2002). Although this is an extremely powerful tool that is common to the hydrocarbon industry, it is also relatively expensive, sometimes intrusive, and is not well suited to all likely injection conditions. Many other industrial techniques (Table 2) are beginning to enter into the CO_2 injection efforts, with the Frio Brine Pilot serving as the first location where multiple techniques will be compared against each other within the same flood (Myer et al. 2003). Many more such tests are needed.

Table 2: MMV technologies proposed at Teapot Dome

Technique	Detection method	Areas of investigation	Status at Teapot Dome
Time-lapse (4D) multi-component seismic	Acoustic	NR	Proposed
Vertical seismic profiling (VSP)	Acoustic	NR	Planned
Cross-well seismic tomography	Acoustic	NR	Planned
Downhole microseismic	Acoustic	NR	Proposed
Electrical resistance tomography	Electrical	NR	Planned
Electromagnetic induction tomography	Electrical	NR	Planned
Soil gas sampling	Chemical	NS, AG	Active
Noble gas tracing	Chemical	NR, VZ, NS, AG	Planned
Other gas tracing (e.g., PFC)	Chemical	NR, VZ, NS, AG	Proposed
Well-head detectors	Chemical	AG	Proposed
Brine sampling	Chemical	NR	Proposed
Subsurface ad surface tilt meters	Physical	NR, AG	Planned
Airborne hyperspectral imaging	Optical	AG	Planned
Space-based monitoring (OCO)	Microwave?	AG	Proposed

NR= Near reservoir, VZ=Vadose zone, NS= Near surface, and AG= Above ground. Active = Currently deployed; Planned = money & team assembled; Proposed = brought forth by research team.

Due to the abundance of preexisting wells, Teapot Dome is well suited to various down-hole approaches (e.g., microseismic monitoring, down-hole active source cross-well tomography). We anticipate proposals to deploy many types of subsurface arrays, including electrical, acoustic, and geochemical suites. This effort is somewhat aided by RMOTC's current research efforts into microdrilling. In addition, a variety of near-surface and surface approaches are in progress. Soil monitoring stations have already been deployed for baseline characterization. Hyperspectral imaging is scheduled to begin at the field in fall 2004 within the context of a methane pipeline leakage study led by RMOTC and the DOE.

Discussion

The unique history of Teapot Dome, specifically its Federal ownership, has several important implications for a scientific program there. To begin, all data sets and experimental results would be public domain. This makes an excellent platform for collaborative research of all kinds, including international collaborators. It also provides a platform for training and public outreach. These are long-term goals of the program, but are not currently organized.

The high well density, abundant data volumes and types, and excellent geological characterization of all units makes it possible to envision and execute a wide range of potential storage experiments. We anticipate an expansion of the scientific program as a consequence of industrial, academic, and government research interests. Although the initial emphasis as outlined is likely to remain Teapot's core scientific mission, the field's great size and flexibility in operations allows for new directions and new emphases to evolve within the context of the needs of the carbon storage community. Such programs might include new materials suitable to subsurface carbon management, geomicrobiological studies in the subsurface, or multi-phase fluid flow experiments. Ultimately the scientific content of such efforts would be independently assessed, but could take advantage of Teapot's unique platform.

Part of the scientific mission is to support stakeholders in their work efforts. Many industrial and governmental groups have scientific concerns about carbon storage that could be addressed at Teapot Dome. We anticipate providing such support to the DOE Regional Carbon Sequestration Partnerships, the national labs, and industrial entities and consortia in the US and abroad. As a well equipped natural laboratory, Teapot Dome could readily address specific concerns in a relatively short time frame.

Conclusions

1. The new Teapot Dome facility presents a unique opportunity to conduct carbon-storage experiments across many geological conditions and scientific disciplines
2. Current science goals include an emphasis on maximizing storage, characterizing leakage risks, and developing monitoring, measurement, and verification (MMV) technology
3. Current proposed research includes injection into the Tensleep Fm. and 2nd Wall Creek Sandstone

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